3. 1. 3. 6 RF Drive and Control System

3. 1. 3. 6. 1 RF Reference Distribution System

System Layout

A block diagram of the RF reference distribution system is shown in Fig. 3.1.3.6.1. The 12-MHz RF reference is distributed to 60 low-level RF (LLRF) control systems of klystron and solid-state amplifier stations (RFQ, buncher, chopper, DTL, STDL, ACS and debuncher) through optical links (E/O, O/E and optical cables). As shown in the figure, the electrical RF reference signal (12 MHz) generated by a master oscillator is converted to optical signals by an E/O, amplified by an optical amplifier, and is then divided into 17 optical transfer lines by an optical star coupler. One optical line provides the RF reference for 4 klystron stations. The transmitted optical signal is divided into 4 by an optical coupler. Each of them is received by an O/E and converted to an electrical signal at each station. The merits of optical transfer are: a) very low loss, b) free of electrical noise, and c) high stability against temperature change. All components of this distribution system will be installed into the klystron gallery.

The accelerating source RF (klystron driving signal) of 324 MHz or 972 MHz is generated by a VCXO with PLL synchronizing with the distributed 12-MHz reference at each local station. Although the fast-change phase jitter is suppressed by the VCXO, for very slow-change phase jitter stabilizing the temperature drifts very important.

To stabilize the amplitude and phase of the field in the accelerating cavity, a digital feedback and feed-forward technique is used in the LLRF control system (See next section).

Optical Fiber

Since the reference RF is delivered trough the optical links, the phase stability depends on the characteristics of the optical components (E/O, O/E and optical fiber). For the optical transfer line, the phase-stabilized optical fiber (PSOF) is required [1]. PSOF has high stability

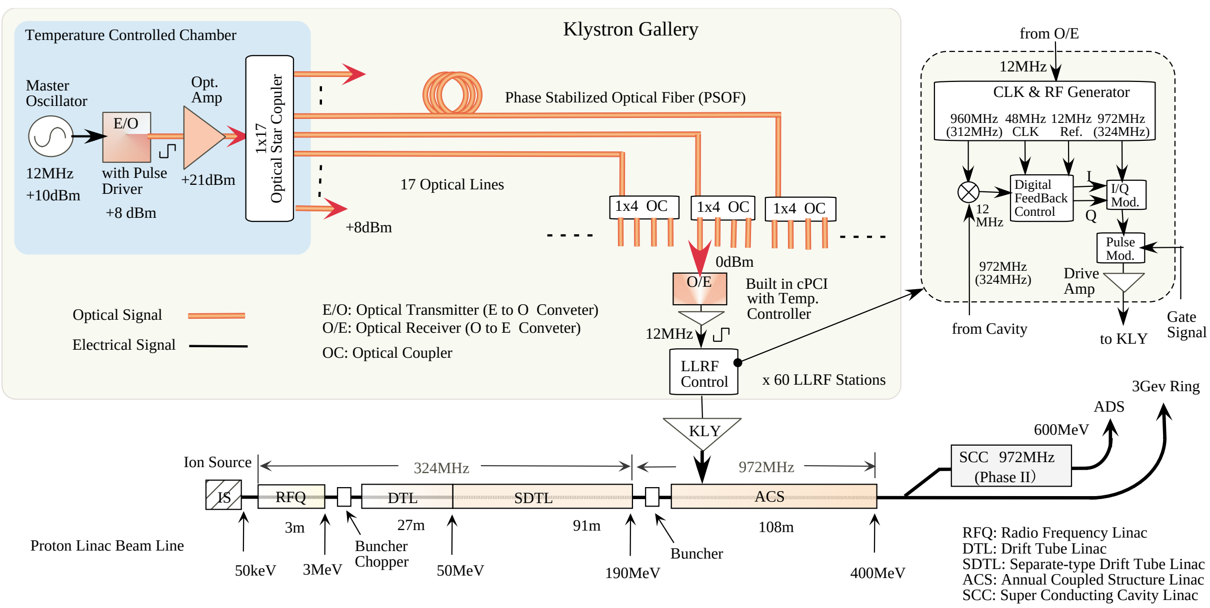

Fig. 3.1.3.6.1: Block diagram of RF reference distribution system

Table 3.1.3.6.1: Main Parameter for PSOF & E/O converter

Optical Fiber	
Wavelength (λ)	1.31 μm or 1.55 μm
Fiber Type	Single Mode Silica Fiber
Cut off Wavelength	1.10 ~ 1.27 μm
Mode Field Diameter	9 ± 1 μm
Cradding Diameter	125 ± 2 μm
Transmission Loss	< 0.5 dB/km (λ=1.31 μm)
Wavelength Dispersion	< ± 4 ps/nm/km (λ=1.31 μm)
Thermal Expansion Coefficient	< 1 ppm/°C

E/O Converter (Optical Transmitter)	
Laser Module Type	Distributed Feed Back (DFB) - LD
Wavelength	1.55 μm
Wavelength Spectrum Width	< ±0.2 nm
Output Power (CW)	> 6 mW
Fiber Type	Single Mode
Modulation Frequency	12 MHz (Direct Modulation)
Automatic Power Control, Temperature Control, Low Noise, Low Power Dissipation are required.	

against temperature changes. The thermal coefficient of PSOF is generally less than 1 ppm/°C, while that of normal fiber is about 6 ppm/°C. In order to reduce the thermal coefficient, PSOF is coated with liquid crystal polymer which has a negative thermal expansion coefficient [2]. The main parameters of PSOF are shown in Table 3.1.3.6.1.

There are two types in PSOF: one manufactured by Sumitomo Electric Ind. Ltd Japan; the other by Furukawa Electric Ind., Ltd Japan. However, these days, only Furukawa Electric Ind. Ltd Japan manufactures PSOF.

The temperature dependence of the transmission delay time of both the Sumitomo and Furukawa PSOF was measured. The result is shown in Fig 3. 1. 3. 6. 2. About 1 ppm/°C and 0.4 ppm/°C were obtained at temperature from 25 °C to 30 °C, respectively. No remark-able difference was observed between 1.31 μm and 1.55 μm wavelength transmission.

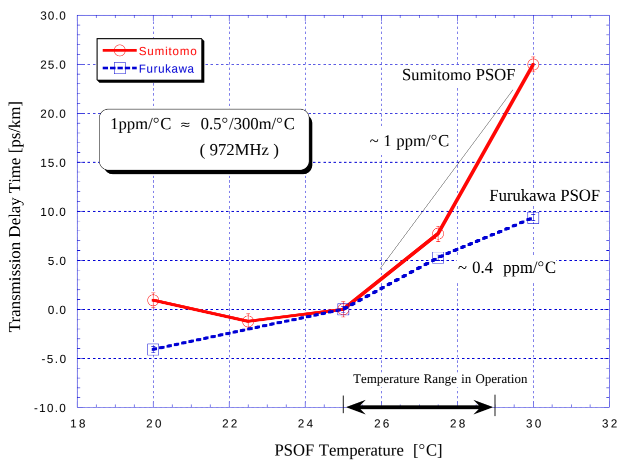

Fig 3. 1. 3. 6. 2: Temperature dependence of the transmission delay time of PSOF

The room temperature will be controlled at 27±2 °C during operation. When the thermal coefficient is 0.4 ppm/°C, a room-temperature change of ±2 °C induces about a ±0.4° phase change for 300-m optical transmission at 972 MHz RF. This characteristic does not satisfy the required stability. In order to keep the phase change due to the optical cable within ±0.1°, the temperature change of the PSOF should be controlled to be ±0.5 °C by a cooling water system.

E/O, O/E Converter

Table 3.1.3.6.1 also shows the required performances as the optical transmitter (E/O). For both of E/O and O/E, the auto temperature control and auto power control are very important. The wavelength of 1.55 µm is selected in order to use an optical amplifier.

With respect to the required stability, Ortel 3540A and 4510A, which are widely used for analogue signal transfer, are candidates as required E/O (optical transmitter) and O/E (optical receiver), respectively. There are few other candidates matching the required performance. In our use, however, Ortel's E/O or O/E has some mismatches; for example, they are suitable for use with higher frequency (12 MHz is too low), the O/E has to be very compact in order to be installed into the cPCI module of the digital feedback system, etc. Thus new optimized E/O and O/E for this linac were designed. A trial product E/O (l = 1.55 µm) was produced by Graviton Ind. Ltd Japan [3], which is called Graviton LD-1500 in this report.

The stability characteristics of the Ortel 3540A, 4510A and Graviton LD-1500 were measured. Fig 3.1.3.6.3 shows the long-term phase stability in 324 MHz signal transmission through the optical link. A phase stability of ±0.04° (±0.12° for 972MHz) was obtained. Fig 3.1.3.6.4 shows the temperature dependence of the delay time of the E/O and O/E. The thermal coefficients of Ortel E/O and O/E are 0.75 and 1.25 ps/°C, respectively, and that of the Graviton E/O is 0.5 ps/°C. From these results, it is needed that the E/O should be operated in a thermal chamber. On the other hand, an O/E is to be built in the cPCI module of the digital feedback system at every drive station. It should be equipped with a peltier device for temperature control.

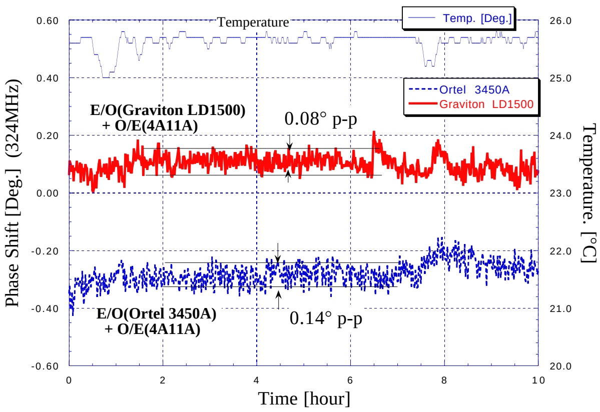

Fig 3.1.3.6.3: Long term phase stability of 324 MHz RF transfer though the optical link.

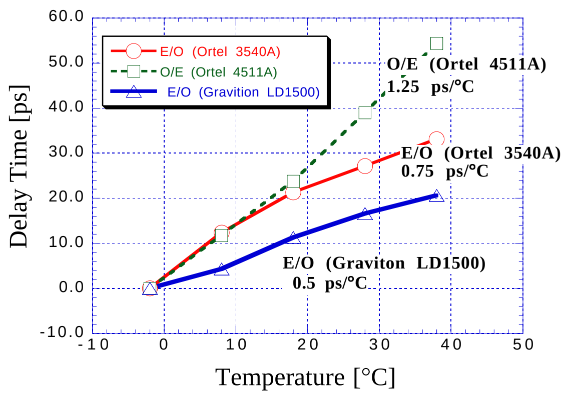

Fig 3.1.3.6.4: Temperature dependence of the delay time of the E/O and O/E.

References

[1] S. Tanaka et al., "Precise Timing Signal Transmission bye a New Optical Fiber Cable", KEK Report 90-5 (1990).

[2] T. Kakuta and S. Tanaka, "LCP coated optical fiber with zero thermal coefficient of transmission delay time", Proc. of International Wire & Cable Symp. (1987) 234.

[3] URL: http://www.graviton.co.jp/

3. 1. 3. 6. 2　Digital Rf feedback system

Field stability of +-1% in amplitude and +-1 degree in phase are required for the RF system in the linac. LLRF system for the 324MHz-cavities is described here. The common devices to 324-MHz system (except RF generator) will be used at the 972-MHz system as many as possible in order to reduce the maintenance work. The digital feedback system is adopted for the flexibility of the feedback (FB) algorism. FPGAs are used for the FB system in order to minimize the FB loop delay (150 ns in the FPGA and total less than 1 µs including rf amplifier, waveguides and cables) [1,2]. DSP board is also utilized for the digital signal processing, the real-time FB monitoring and the communication between FPGA and host cpu.

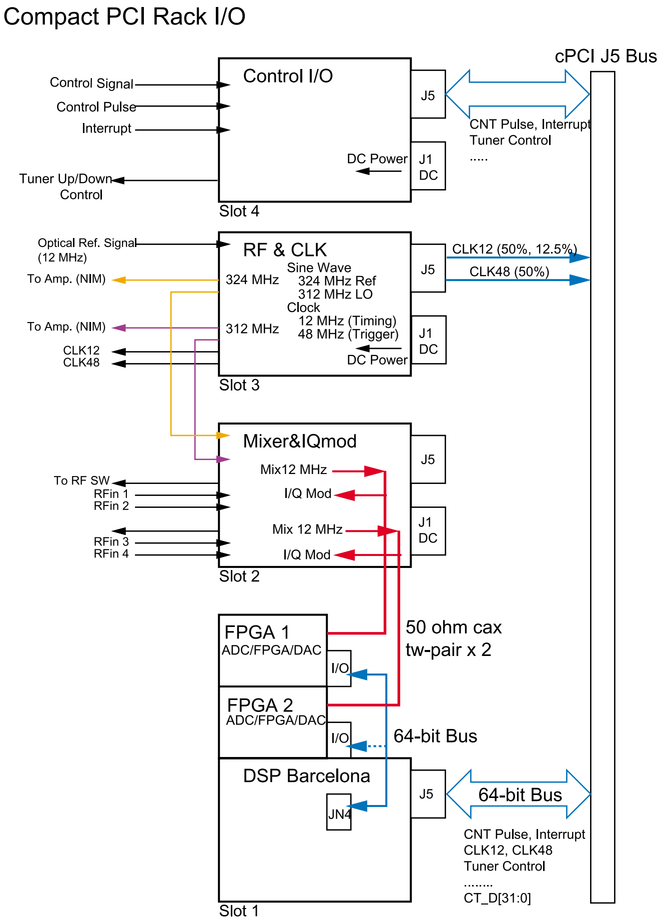

Fig. 3.1.3.6.2.1. Schematic of the cPCI devices

All the LLRF system is installed in the compact PCI (cPCI). Total five boards (CPU, DSP with FPGA, RF&CLK, Mixer&IQmod, control I/O) will be used as shown in Fig.3.1.3.6.2.1. The timing signals, trigger signals, and control I/O are transferred through the user Bus (J5) in the cPCI rack.

LLRF feedback hardware

(1) RF and Clock board (RF&CLK)

The RF and clock generator receives the master 12 MHz optical signal from the master

Table 3.1.3.6.2.1 Hardware specification

RF&CLK	
RF input	12 MHz optical
RF output (324 MHz)	10 dBm
LO output (312 MHz)	10 dBm
I/O Connector	50 Ohm SMA(F)
Mixer&IQmod	
Mixer	
RF input	0dBm
LO input	10 dBm
Input connector	50 Ohm SMA(F)
IQ modulator	
RF input	10 dBm
I/Q component	DC~2MHz (-3dB)
RF output	Max. 10dBm
I/O connector	50 Ohm SMA(F)

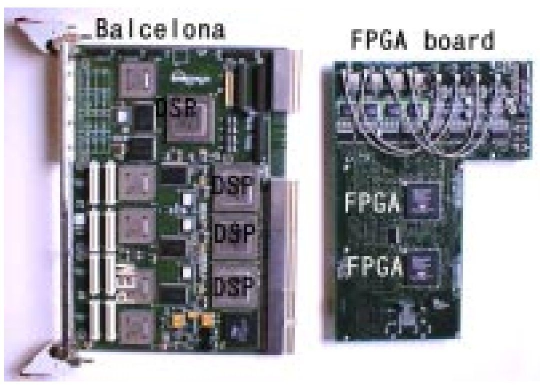

Fig.3.1.3.6.2.2 Photograph of DSP board (Barcelona) and PEM-FPGA board

oscillator. Timing (f_{Tim}, 12MHz), trigger (f_{Trig}, 48MHz), LO (f_{LO}, 312MHz), RF (f_{RF}, 324MHz) signals are generated from the master 12 MHz signal with phase locked loop (PLL). The input/output specifications are summarized in Table 3.1.3.6.2.1.

(2) Mixer and IQ modulator board (Mixer&IQmod)

The rf drive signal (324 MHz) delivered from the RF&CLK board is modulated through the IQ modulator (AD8345). The rf signal is transmitted to the cavity through the RF amplifiers (a low level rf amplifier and a klystron). The rf output from the cavity is down-converted to IF signal by active mixer (AD8343). The IF signal (12MHz) has a good resolution for monitoring the chopped beam (~1.2 MHz). Both IQ modulator input and mixer output are directly connected to the adjacent PEM-FPGA board. The input/output specifications are summarized in Table 3.1.3.6.2.1.

(3) DSP board

DSP board Balcelona (Spectrum Signal Processing Inc.), where the four DSPs (TI C6701) are

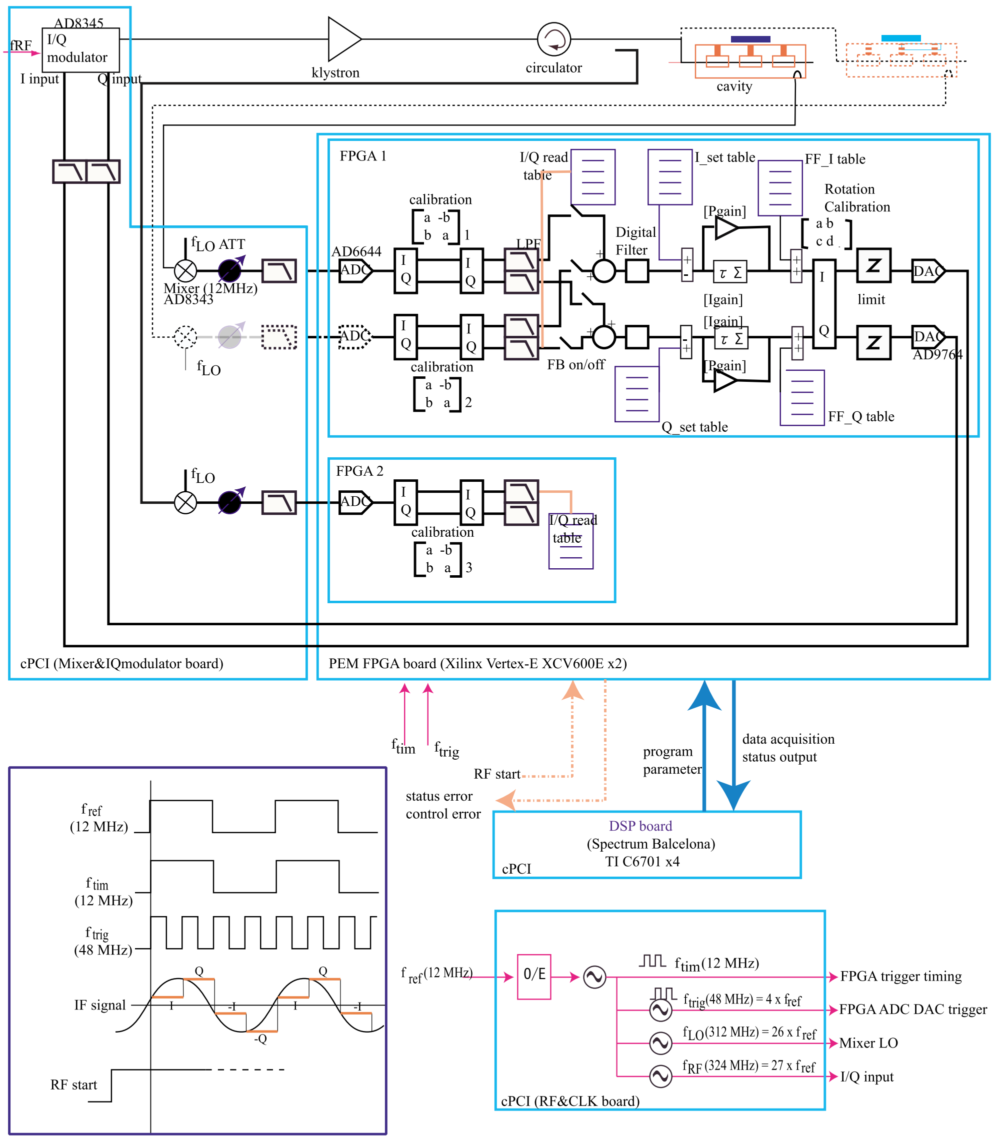

Fig. 3.1.3.6.2.3. Schematic of the digital feedback algorism

installed, are adopted and FPGA board is installed as PEM (Processor Expansion Module). DSP board handles the program/parameter load to the FPGAs and data acquisition from FPGAs. The cavity tuner is also controlled by DSP board.

(4) FPGA board

FPGA board includes two FPGAs (Xilinx XCV600E). Each FPGA is connected to two 14bit-ADCs (AD6644) and two 14bit-DACs (AD9764). Digital feedback is carried out through one of the FPGAs (FPGA1). Another FPGA (FPGA2) measures the I/Q components of the klystron output (in front of the cavity coupler) for the cavity tuner control. The photograph is shown in Fig.3.1.3.6.2.2.

LLRF feedback software

(1) Digital feedback software (FPGA1)

Digital feedback calculation is performed at FPGA1. The simple PI control is adopted for the feedback so as to minimize the feedback delay. The algorism is schematically shown in Fig.3.1.3.6.2.3. The IF signal (12MHz) is converted to the 14bit digital with 48 MHz sampling trigger. The values are defined to I, Q, -I, -Q, step by step [3] (Fig.3.1.3.6.2.3). Measured I/Q components are rotated for the loop phase calibration. In case of SDTL, where two cavities are driven by a klystron, the vector-sum (or weighted vector sum) is applied. The set tables (FB and FF) are given every 1 _s during rf pulse and the measured data are stored in the FPGA memory. The input/output data are summarized in Table 3.1.3.6.2.2.

(2) RF output field measurement (FPGA2)

The I/Q components of the rf output from the klystron is measured at FPGA2. The algorism is the same to FPGA1. The measured data are sent to the DSP through FPGA memory. The values are converted from I/Q components to the amplitude and phase in the DSP. The phase difference between the cavity and the klystron is compared to those at on resonance. In case the error is higher than the specified value, DSP controls the cavity tuner.

Table 3.1.3.6.2.2 FPGA I/O

FB set table (I,Q)	14bit depth 1024 (every 1 _ s, 0~1024 _ s)
FF set table (I,Q)	14bit depth 1024
Proportional gain	8 bit
Integral gain	8 bit
Calibration matrix	8 bit , 2x2 matrix
Limitter (I,Q)	14 bit
Cavity field monitor	14bit depth 2048/4096 (every 0.5_ s/0.25_ s)
Klystron field monitor	14bit depth 2048/4096

References

[1] Shozo Anami, et al., “DIGITAL FEEDBACK FOR THE RF SOURCE OF THE JHF 60-MEV LINAC”, Proceedings of the 25th Linear Accelerator Meeting in Japan, 207 (2000).

[2] Shinichiro Michizono, et al., “RF FEEDBACK SYSTEM FOR THE PROTON LINAC AT THE KEK/JAERI JOINT PROJECT”, Proceedings of the 26th Linear Accelerator Meeting in Japan, 85 (2001).

[3] T.Schilcher, "Vector Sum Control of Pulsed Accelerating Fields in Lorenz Force Detuned Superconducting Cavities", August 1998, TESLA 98-20.

3. 1. 3. 6. 3 Test of feedback system

Feasibility of the feedback control of amplitude and phase was demonstrated for DTL test cavity using analogue modules with two feedback loops: the major loop is for DTL cavity and the minor loop is for klystron. The proportional and integral (PI) control using I/Q modulator and demodulator was adopted. The input power of the cavity was 400 kW.

The measured stability in a pulse was 0.38% rms and 0.95% peak in amplitude and 0.24° rms and 0.71° peak in phase. The long-term stability was 0.03% rms (0.18% peak) for amplitude and 0.24° rms (0.71° peak) for phase. The pulse response with electrically simulated “beam loading” was measured using the “beam loading test box” [1]. The results are shown in Fig 3.1.3.6.3.1. Except for the part of rise and fall of the pulse and start and stop of the beam loading, almost the flat shape was obtained for both amplitude and phase. Residual ripple at the start and stop of the beam loading is to be rejected with feed forward control. The bandwidths of the feedback loop were measured for the drive amplifier, the klystron and the DTL tank by measuring the frequency response for amplitude-modulated input signal. The measured bandwidths are 53 MHz, 1.2 MHz and 18 kHz, respectively for these feedback-controlled devices.

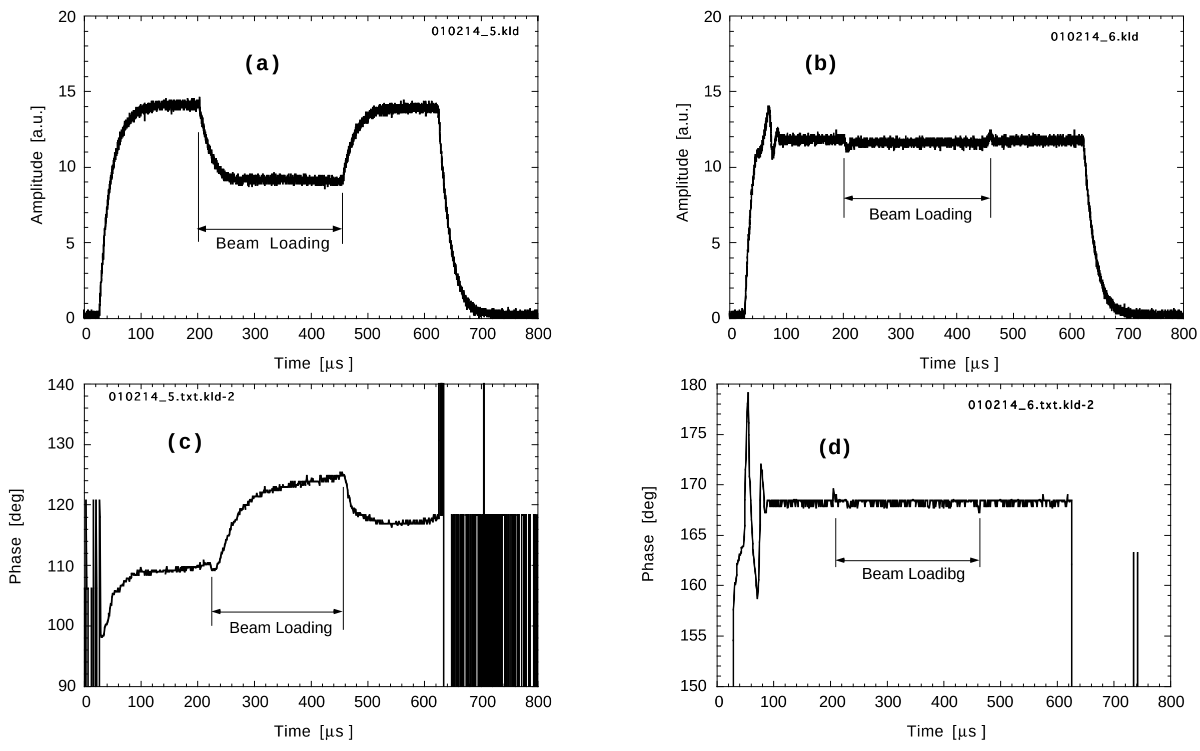

Fig.3.1.3.6.3.1 Pulse response with electricaly simulated beam loading, (a) amplitude without feedback, (b) amplitude with feedback, (c) phase without feedback, (d) phase with feedback.

Reference

[1] R. J. Pasquinelli and B. Chase, “Linac Low Level RF (LLRF) Operating Procedure”, Internal memo, Fermi National Accelerator Laboratory, (1994).